THE UNUSUAL MOVEMENT OF THE GULF OF MEXICO CYCLONE, APRIL 10–13, 1956

HENRY R. McQUEEN AND WILLIAM A. RAMMER

National Weather Analysis Center, U. S. Weather Bureau, Washington, D. C.

1. INTRODUCTION

The northern half of the Gulf of Mexico is a well-known source region for the development of cyclones during the cooler half of the year. The maximum frequency of occurrence is reached during the winter months, then decreases to slightly under one occurrence per month in April, according to Saucier [1]. Both directon and speed of movement of these Lows vary greatly not only with the season of the year but at times with the individual storms. An accurate prognosis of these cyclones is of the utmost importance to the people of the States bordering the Gulf of Mexico and the Atlantic Ocean, a region containing nearly one-third of the population of the United States. Anticipation of the vagaries of these storms is one of the most difficult problems of the prognostic analyst and of the district, State, and local forecasters.

The synoptic situation of April 10–13, 1956, furnishes an excellent example of the acceleration, deceleration, stagnation, cyclogenesis, and deepening that may occur during the life of one of these Lows. Further complicating this situation was the development of a cold core Low during this period over the Carolinas. This storm was investigated because during its life along or near the east coast the actual track deviated considerably from the expected path. The resultant error in the forecast track was partially responsible for the over-forecasting of precipitation in the northeastern States. In this study a few factors associated with the erratic behavior of this storm, as well as a general comparison of prognostic techniques, and an actual comparison of the prognostic charts from the National Weather Analysis Center and the Joint Numerical Weather Prediction Unit are presented.

2. ANTECEDENT CONDITIONS, APRIL 7–9

A moderately intense cold front that had crossed the Pacific Ocean began moving onshore over the northwestern portion of the State of Washington by the morning of April 7, 1956. By the morning of April 8 a weak low pressure center had developed over portions of northwestern Wyoming and southeastern Montana. This Low had formed at the intersection of a moderate Pacific polar cold front and an old stationary front along the eastern slope of the Rockies. During this period of 24 hours the center of the cold air on the 1000–500-mb. thickness chart had a value near 17,400 ft., while the value along the shear line, which indicated the position of the cold front, was near 18,200 ft. At 500 mb. the winds on the back side of the associated trough indicated a rather rapid transport of cold air southward.

The surface low pressure center was located over the Texas Panhandle by early morning of April 9, having plunged southward along the eastern slope of the Rockies. In the same period the attendant cold front had been driven rapidly southward in conjunction with the continued advection of cold air aloft and the maritime polar front had crossed the southern borders of New Mexico and Arizona. To the north of the low center the occluded portion of the surface front was being dissipated almost as rapidly as it formed while the Low was plunging southward.

Generally the shear across the warm front until this time had remained moderate in intensity but by 1500 GMT of April 9, the gradient across the front was weakening and another shear zone was intensifying farther south. This developing shear was located along an old maritime polar front that had been lying more or less stationary in the Gulf of Mexico and eastward into the Caribbean and the Atlantic Ocean. The thickness gradient not only continued to be maintained to the rear of the cold front but intensified, so that the frontal classification was increased to strong.[1] Thus a change from moderate to strong intensity of the front occurred notwithstanding that it had been driven southward some 1,200 miles during the past 2 days. The frontal intensification resulted from two factors: first, a continued strong advection of cold air southward, and second, the gradual moderation of temperatures behind the front. The latter was indicated by a rise of nearly 600 ft. in the thickness value immediately to the rear of the front, and the former by the persistency of the 17,600-ft. height line around the center of the cold air as it moved southward.

Over the central and eastern portions of the United States prior to 1230 GMT April 9, there had been an intense

[1] At the National Weather Analysis Center the criterion used for the determination of the intensity of fronts is the shear across the front of the 1000–500-mb. thermal winds; a difference of 25–49 knots indicates a front of weak intensity, 50–79 knots, moderate, and 80 knots or greater, strong intensity.

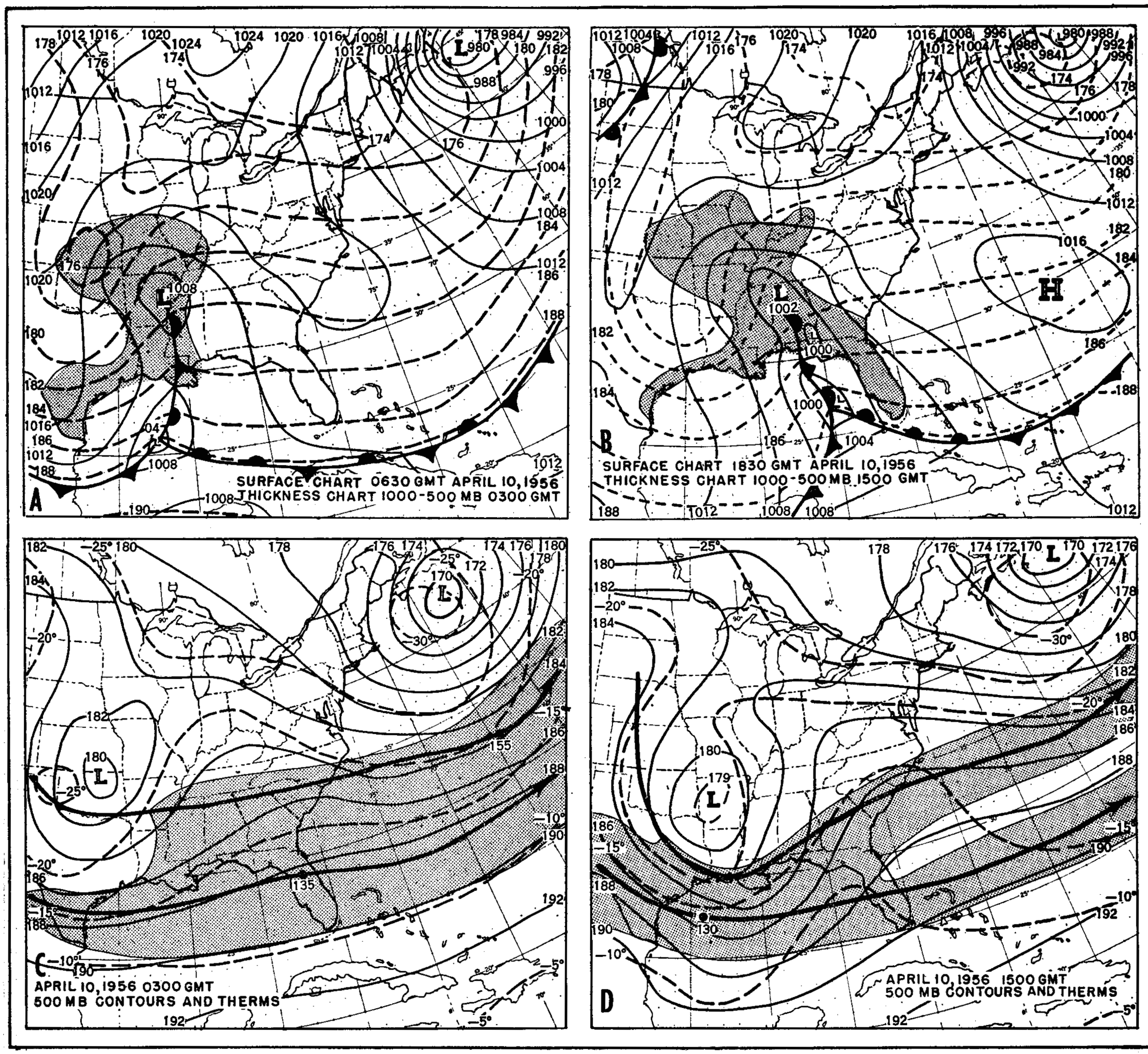

FIGURE 1.—Synoptic patterns for April 10, 1956. (A) 0630 GMT surface chart with 1000–500-mb. thickness for 0300 GMT indicated by dashed lines. Shading covers precipitation area during preceding 24-hour period. (B) 1830 GMT surface chart. (C) 0300 GMT, 500-mb. chart. Heavy arrowed lines indicate 200-mb. jet stream. Shading covers regions of 100-knot or higher wind speeds with position and value of maximum shown by numbers near jet stream. (D) 1500 GMT, 500-mb. chart.

low pressure center at the surface and aloft. But by the afternoon of April 9 it was moving off the east coast. A moderately intense anticyclone separated the two Lows early in the period but this High had gradually diminished, becoming a weak ridge as it moved northeastward between the two depressions.

3. SYNOPTIC FEATURES, APRIL 10–13

Late in the day on April 9 or early morning (GMT) of the 10th the maritime polar front coalesced with the old stationary front. This occurred either in the extreme southern portion of Texas or over the western Gulf of Mexico near the Texas coast. From the point of juncture, northward to the center of the Low, the cold front had rapidly assumed occluded characteristics. All signs of the northern warm front that earlier had been a segment of the original frontal system associated with the Low had dissipated.

The 0300 GMT 500-mb. chart (fig. 1C) of April 10 presented a trough, ridge, trough, ridge, and trough pattern

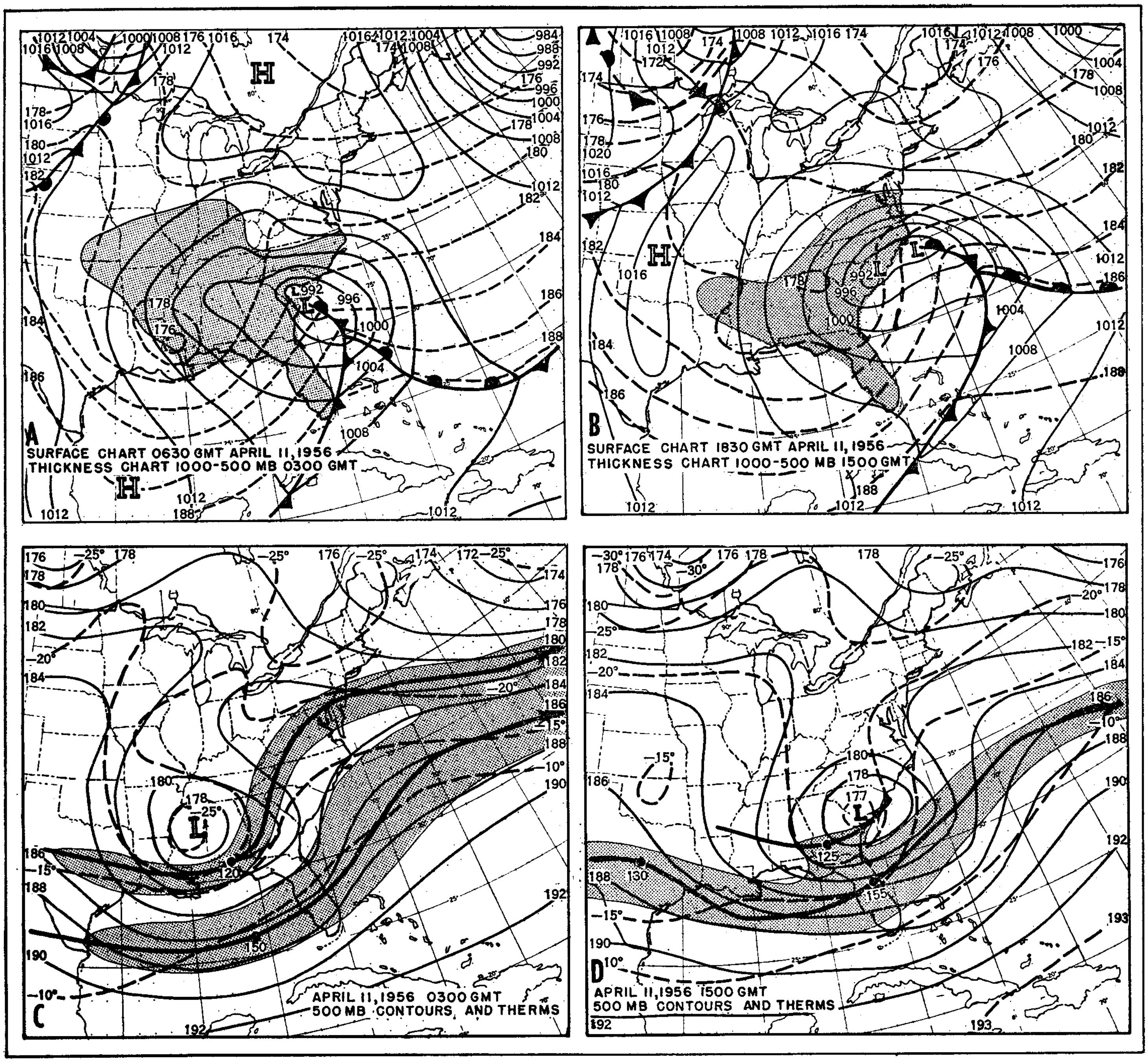

FIGURE 2.—Synoptic patterns for April 11, 1956.

between the 25th and 45th parallels from 60° to 130° W. All troughs had at least one closed height contour about the central area and the central height values within these closed contours rose progressively westward. Both ridge areas were rather weak with the westernmost one being the more pronounced of the two. The upper low center with which we are concerned (fig. 1C) was located near Tulsa, Okla., with the trough extending south-southwestward. An area of cyclonic vorticity was indicated south of this center on both the 500-mb. and the 1000–500-mb. thickness charts (fig. 1A and 1C). At the same time an area of confluence was located near the juncture of the four States of Arizona, New Mexico, Utah, and Colorado. The confluence area remained rather well defined during the next 24 hours and this, along with the intensifying gradient, aided in producing westerly winds of high speed, south of the upper low center.

During the next two days the winds at 500 mb. ranged from 60 to 120 knots with numerous observations indicating westerly winds of 70 to 80 knots. Much less pronounced contour gradients were prevalent during this period to the east and west of the low center (figs. 1C,

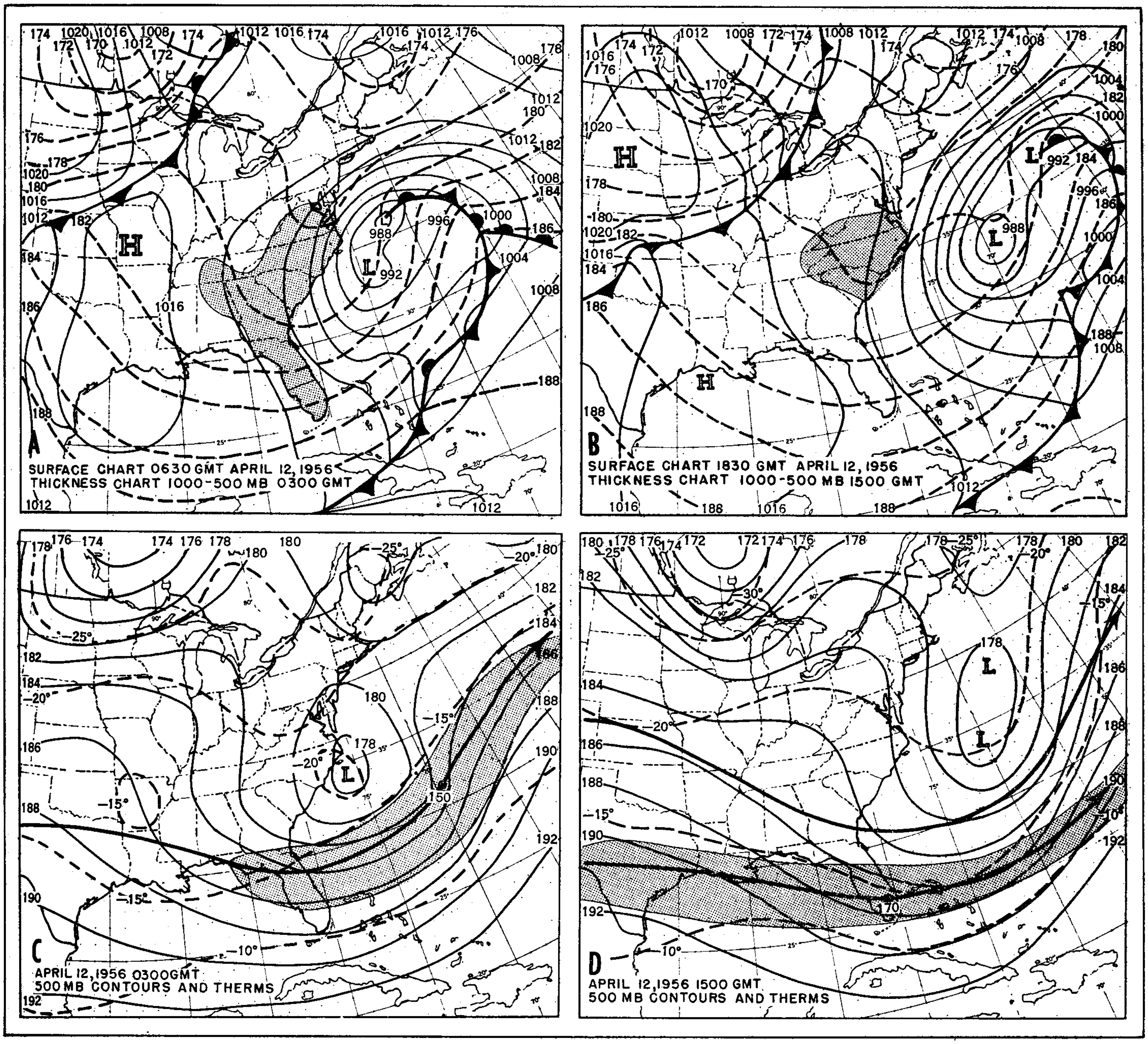

FIGURE 3.—Synoptic patterns for April 12, 1956.

1D, 2C, 2D, 3C, 3D) with the prevailing winds less than one-half the speed of the westerly flow. On the surface chart for 1230 GMT of the 10th, deepening had occurred at the point of occlusion, now over the central portion of the Gulf of Mexico, and the central pressure was 998 mb. (fig. 4). The front extending north of this center continued to be maintained and was active in producing heavy showers and thunderstorms as it moved eastward. By 1500 GMT of the 10th (fig. 1D), the 500-mb. center was near Little Rock, Ark. Slight intensification had occurred at the center of the upper Low and the attending trough was moving to the east ahead of this center. The upper ridge to the east of the Low showed a slight tendency to strengthen and to build northward.

Within the next 12 hours, ending at 0030 GMT of the 11th, the central sea level pressure of the cyclone lowered to 994 mb. (fig. 4) and was located approximately 80 nautical miles north of Tampa, Fla. That it had become an unusually intense storm can best be realized by the comparison of the existing sea level pressure records for April [19] with the barometric values that occurred during this storm. At Key West, Fla., a low reading of 1001.0 mb. was 2.3 mb. lower than the previous record; at Tampa, Fla., a reading of 999.3 mb. was 2.0 mb. lower;

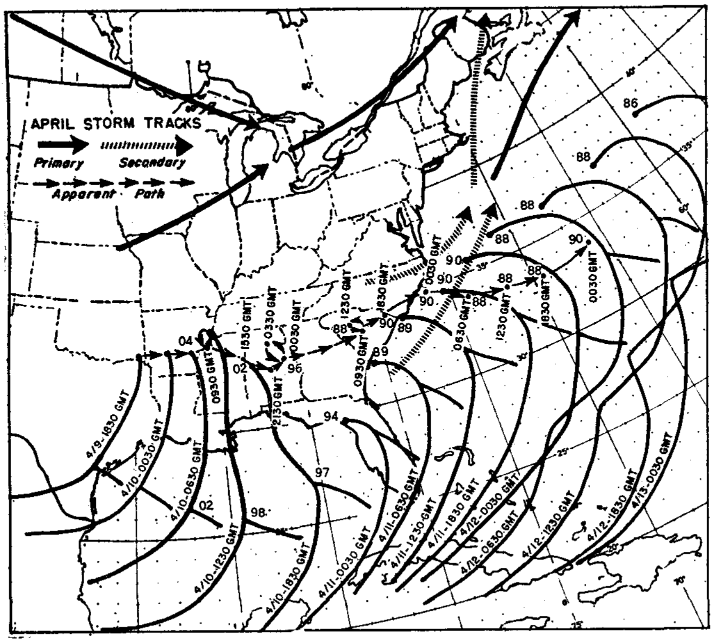

FIGURE 4.—(A) Surface storm centers and frontal positions at 6-hour intervals from 1830 GMT, April 9 through 0030 GMT, April 13, 1956. Pressure values of centers are shown by numbers (with hundreds and thousands values omitted) near the point of occlusion or at the northern end of the front. Apparent track of the old low center is shown by small arrows. Heavy solid arrows indicate the primary April track for cyclones and the shaded arrows the secondary April track for cyclones (after Klein [8]). (B) Positions of 500-mb. trough (solid) and 700-mb. trough (dashed), 1500 GMT, April 9 through 1500 GMT, April 12, 1956.

and at Apalachicola, Fla., the reading was near its all time low of 997.6 mb. for April. Some of the stations in Georgia and South Carolina also reported sea level pressures that were lower than their previously reported low values for any April, such as Savannah with a reading of of 989.2 mb. While the synoptic reports did not indicate winds of high speed over Florida, the maximum winds reported on the 10th or 11th were generally between 35 and 40 m. p. h.

The 0300 GMT 500-mb. chart of the 11th (fig. 2C) failed to indicate further building of the ridge ahead of the Low. In fact, a reversal of that trend appeared to be in progress as the ridge continued its eastward motion. During this time the 500-mb. Low was intensifying and the speed of its eastward motion was increasing. The trough, with its easternmost position over the Atlantic Ocean, by now had been carried far ahead of the low center.

By 0030 GMT of the 11th (fig. 4), the front which had connected the two surface pressure centers had apparently dissipated although a well defined trough remained. This old Low had continued in a general eastward direction but its movements were unusual and erratic as it traversed the area from Memphis, Tenn., to Spartanburg, S. C. Between 0630 and 1830 GMT of the 10th, the 3-hourly surface charts indicated that a loop or node in the track of the Low had occurred near Memphis, Tenn., and then the center moved rapidly eastward (fig. 4). A similar loop or node was again indicated near Birmingham, Ala., around 0030 GMT of the 11th (fig. 4). At the same time a well-developed trough extended from this low center across northern Georgia into northern South Carolina. Between 0630 and 1530 GMT of the 11th another loop or node occurred in the Spartanburg, S. C., region (fig. 4). It was only after careful analysis of the 3-hourly charts that these loops or nodes became apparent. That this Low moved across the eastern half of the country was difficult to discern and not until the preparation of the 3-hourly isallobaric charts, was reasonable proof forthcoming. This was an unusual and complex situation to analyze and it is not surprising that the surface chart for 0930 GMT of the 11th showed the Gulf storm separating into two Lows. However, upon close examination it is definitely believed that the Low which appeared south of Spartanburg was either associated with the old surface Low previously west of the mountains and rejuvenated in the Spartanburg area, or that cyclogenesis occurred within the region in association with the upper cold Low that was over the area.

From the data available the answer to this question concerning the movement of the surface Low cannot be definitely ascertained but the 3-hourly isallobaric charts suggest that a jump may have occurred. However, an intense and well-developed low center was formed and was maintained east of the Appalachians. This Low moved off the eastern seaboard early on the morning of the 12th (fig. 4).

The Gulf of Mexico cyclone, by 0630 GMT of the 11th, was near Savannah, Ga., and moving in a northeasterly direction with the central pressure near 989 mb. Sea level pressures to the north and east of the Low were falling rapidly, with 6-hourly pressure falls ranging from 10.0 to 15.0 mb. at many stations ahead of the storm.

From 0300 to 1500 GMT of the 11th, the upper Low continued its rapid eastward motion but with its trough becoming less pronounced and moving more slowly. After the death of the occluded front in the northern-centered Low during the preceding 6 hours, this cyclone had become a well-developed cold-core Low with a pronounced and descending tropopause center. It was during this period that the upper center of the Low apparently reached its maximum strength with a height of less than 17,700 ft. at the 500-mb. level. Concurrently the west winds at this level attained the maximum reported velocity of 120 knots. The distance between the surface position of the Gulf of Mexico storm and the location of the cold-core center had decreased approximately 50 percent during the past 24 hours.

By 1230 GMT of the 11th (fig. 4) there had been a definite alteration in the path of the surface Low for it was now moving in an east-northeast direction. The Low continued to swing to a more easterly direction during the next 12 hours. But the central value remained practically unchanged during this time with near record pressures being reported. During April 11 (GMT), as the storm skirted the coast line south of Hatteras, high winds predominated. The intense pressure gradient in this area resulted from the deepening of the cyclone and the northward movement of the storm center. Winds along the Carolina coasts reached speeds of 75 m. p. h. At Charleston, during this period, a new maximum wind velocity for April was recorded [2], with a 1-minute average of 65 m. p. h. from an easterly direction. In the Norfolk, Va., area, gale winds began at 1345 GMT of the 11th and continued until 0330 GMT the next day [3], a period of nearly 14 hours. The maximum average wind speed for a 1-minute period was 62 m. p. h. from a northerly direction. Considerable damage and flooding resulted from high winds and tides in and around Norfolk. Further details concerning this will be mentioned in section 8.

As the old low center now associated with the cold-core cyclone moved off the east coast it was partially depressed southeastward by the strong northeast flow. Also it appears that the southeast movement may have been due in part to the tendency of two cyclones of equal intensity to revolve around each other in a counterclockwise sense [4]. However, in this double-centered storm it appears that only partial revolution occurred. The old center then gradually recurved toward the east and northeast maintaining a relatively constant distance to the southwest of the Gulf of Mexico Low. In the upper air the rapid eastward movement of the cyclone continued through 0300 GMT of April 12 (fig. 3C) with indications of a slight decrease in the intensity of the central value. However this fact is not definite as the center was then over the ocean. The trough ahead of the low center continued to decelerate and was assuming a more normal position, while a new trough was developing in the southwestern quadrant. It also appeared at this time that the Low was elongating since a new center was in the process of formation ahead of the old center. By 1500 GMT the elliptical appearance had become more pronounced (fig. 3D).

4. THREE-HOURLY PRESSURE CHANGE

The 3-hourly pressure change tendencies during the formative stage of the Gulf of Mexico cyclone indicated an isallobaric field similar to that normally expected in a cyclogenetic area, while the original storm center in Arkansas had 3-hourly falls of from 1 to 2 mb.[2] At 0630 GMT April 10 katallobaric tendencies of between 3 and 4 mb. appeared in the Memphis area and similar values covering a slightly larger area were present near 26° N., 91° W. (See fig. 5 for path of movement.) By 1230 GMT the northern katallobaric area had moved to the vicinity of Tupelo, Miss., with the falls less intense in that region than in the area southeast of New Orleans where falls had increased to values of 5 and 6 mb. near the center. The

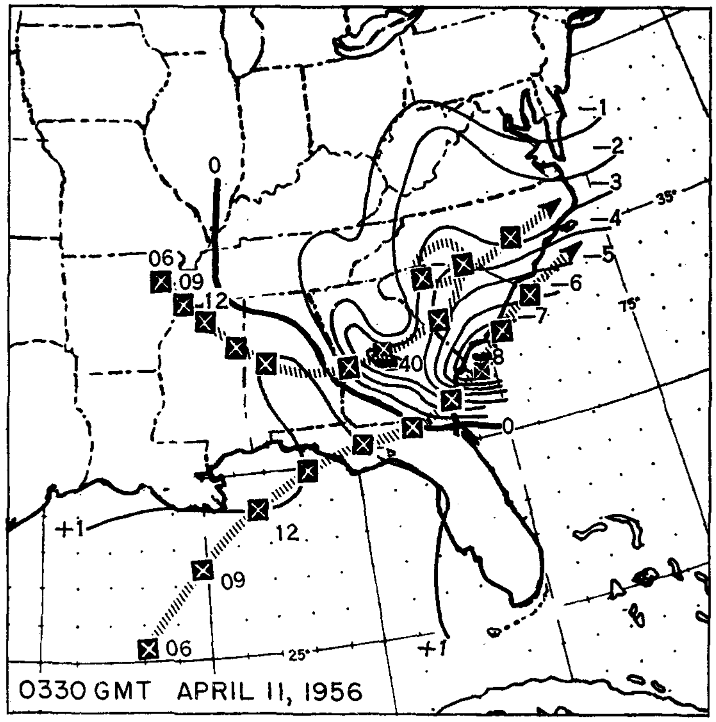

FIGURE 5.—Three-hour isallobars (labeled in whole millibars) for 0330 GMT, April 11, 1956, corrected for diurnal pressure changes. Shaded lines indicate path of katallobaric centers, 3-hour positions indicated, beginning with 0630 GMT, April 10, 1956.

area of the katallobaric field of the deepening Low in the Gulf of Mexico had increased and appeared to be merging with the northern katallobaric field by 1830 GMT, April 10. But a definite katallobaric trough continued to be present in the region from Meridian, Miss. to Montgomery, Ala., with the main fall center of 5 and 6 mb. in the vicinity of Tallahassee, Fla. However, by the 0030 GMT chart of the 11th (fig. 5) the 3-hourly katallobaric field had separated into two distinct centers. The fall area associated with the Gulf Low was located east of the Georgia coast with central falls greater than 6 mb. while the second center, near Phenix City, Ala., had falls of 4 mb. These katallobaric areas continued to advance east-northeastward during the next few charts with the central falls approaching 8 to 10 mb. in a 3-hourly period.

Between the hours of 0630 GMT and 1530 GMT of the 11th the katallobaric field associated with the Gulf of Mexico storm advanced steadily toward Cape Hatteras. During the same time the field associated with the old Low moved from Columbia, S. C., to near Charlotte, N. C. At 0930 GMT the katallobaric center was approximately 30 nautical miles southeast of Charlotte, N. C.; and then during the next 5 hours this center apparently circled that city within a radius of 30 nautical miles. It is opined that it was during this period that the old surface Low either jumped or was rejuvenated east of the mountains and that this katallobaric loop or node reflected this eastward jump or rejuvenation of the surface portion of the cold-core Low.

[2] All 3-hourly values mentioned have had the diurnal corrections applied.

5. THICKNESS PATTERN

Prior to the development of the Gulf of Mexico storm the 1000–500-mb. thickness values were between 200 and 600 ft. below the April normal over the southeastern quarter of the United States and the northern sector of the Gulf of Mexico. The advection of additional cold air on the 9th and 10th of April into this area, and to the rear of the maritime polar front not only helped to maintain but also to increase the departure from normal of the thickness pattern. Thus a strong thermal field was associated with this wave development from its inception (fig. 1A, B).

The continued advection of cold air to the rear of the advancing maritime polar front produced an anomaly of −800 ft. in the 1000–500-mb. thickness values near New Orleans at 0300 GMT of the 11th. Ahead of the warm front the departure from normal was small. The upper wind flow pattern indicated that there would be no large-scale advection of warm air in advance of this front, tending to preclude the building of any pronounced ridge ahead of the Low.

During this period the cold front was delineated by the 18,800 ft. thickness line (fig. 2A, B) while the thickness value encircling the center of the cold air ranged from 17,600 to 17,800 ft. with the distance between the two extremes approximately 600 miles. Such a gradient would indicate thermal winds with an average velocity of 90 knots and a speed near 100 knots along the front. There being little or no thickness gradient south of the front, a thermal shear in excess of 80 knots would ensue. This would require the cold front to be classified as strong.

6. TROPOPAUSE

During the period from the 9th to the 12th of April, a field of below normal tropopause heights to the west of the original surface low center reached a minimum almost vertically above the low centers at 700, 500, 300, and 200 mb. At 0300 GMT of the 10th, this low tropopause was centered in the vicinity of Wichita, Kans., and by 1500 GMT of the 10th had moved to near Springfield, Mo., with the height dropping to 25,000 ft. On the 11th of April at 0300 GMT the center was near Birmingham, Ala., the central height value continuing near 25,000 ft. But by 1500 GMT, the tropopause center had moved eastward to near Charleston, S. C., with the height lowering to 23,000 ft. or a pressure of 416 mb. and a temperature of −37° C. Earlier, Montgomery, Ala. confirmed this low tropopause with a pressure of 350 mb. and a temperature of −42° C. That 23,000 ft. was an extremely low tropopause for Charleston is indicated by a comparison with available tropopause data for Norfolk, Va., which, being north of Charleston, would be expected to experience low tropopauses more frequently than Charleston. At Norfolk over 95 percent of tropopause heights are above 27,000 ft. during the months of March, April, and May [5]. It was also noted that a 500-mb. temperature equal to or lower than the −23° C. observed at 1500 GMT, April 11 at Charleston, has been observed only 15 percent of the time at Norfolk [5] where the 500-mb. temperature is normally lower than at Charleston.

7. PRECIPITATION

Storms that develop in the Gulf of Mexico are one of the main sources of precipitation for the southern States and often produce some of the larger rainfall or snowfall accumulations in the eastern seaboard States. It is for this reason that the prognoses of movement and location of Gulf of Mexico storms are so important to the eastern residents of our nation.

One can easily see by a rapid check of the precipitation totals that the production of precipitation by this storm was similar to most other Gulf of Mexico cyclones. The 24-hour rainfall totals ending at 1230 GMT, April 10, indicate widespread precipitation over the middle and lower Mississippi Valley, the lower Missouri Valley, the Arkansas Valley, and a portion of the Red River Valley with the larger totals having occurred in the western portion of the Gulf Coastal Plains (see figs. 1, 2, and 3, A and B). In this Gulf Coast area, 24-hour totals were generally from 1 to 2 inches with amounts locally reaching 5.00 inches at Cadiz, Tex., and 3.00 inches at Ingleside, Tex. A few totals in excess of 1 inch were also recorded in the Ozark Plateau area.

By the 1230 GMT chart of April 11, the Gulf of Mexico storm center had become fully developed and had swung northeastward, crossing the northern portion of the Florida Peninsula. The attending rainfall pattern also continued to be widespread as it advanced eastward. During the 24 hours previous to 1230 GMT of the 11th precipitation had occurred over practically all of the southeastern quarter of the United States. East of the Appalachians the northern edge of the precipitation area was sharply defined in southern Virginia. A few of the larger rainfall totals were: Columbia, S. C., 3.64 inches; Charleston, S. C., 2.21 inches; Lincolnton, Ga., 2.50 inches; and City Office at Miami, Fla., 2.52 inches. It was this storm that brought temporary relief from a serious drought condition in Florida and eased the treacherous forest and brush-fire hazards. During the 57 days preceding this storm the total precipitation at Miami, Fla., was only 0.26 inch and the rainfall had occurred at widely spaced intervals.

The Gulf of Mexico storm center continued its eastward movement and by 1230 GMT April 12 was located 600 nautical miles east of Norfolk, Va. The related cold-core Low that had developed over the southern Appalachians the preceding day brought heavy rains as it moved eastward in the wake of the Gulf storm. In the 24 hours ending at 1230 GMT of the 12th precipitation had occurred over the southern Coastal Plains and the southern Appalachians with totals in excess of 1 inch reported in North

Carolina and southeastern Virginia. Thus with the eastward movement of these centers the threat of heavy rains from Virginia northward had ended. The demarcation line between measurable precipitation and no precipitation had remained sharply defined along the northern border of Virginia. Washington, D. C., reported only a trace of precipitation from the double-centered storm.

According to climatological records the accumulated rainfall totals from the storm ranged from 1 to 12 inches in North Carolina and locally snowfall totals in the North Carolina mountains reached a depth of 11 to 12 inches [6].

8. EFFECTS OF THE STORM

Beneficial results and destructive effects occurred from this storm. In southern Florida it was the first productive precipitation for nearly two months, thus reducing the prevalent fire hazards and furnishing much needed moisture. At the same time it produced local wind damage. Miami reported an apparent tornado in nearby areas shortly after 2330 GMT of the 10th, but the damage reported from later investigation was classified as wind damage. Another tornado was reported in the vicinity of St. Simon Island off the southeastern Georgia coast at 0430 GMT of the 11th. This was later classified as a waterspout. Along the Florida coast some damage was done to barges and small boats. Minor damage prevailed along much of the coastal sections north of Florida due to high winds and tides. However, the bulk of the damage of this storm occurred from Hatteras northward with the greatest havoc occurring in and around Norfolk, Va.

In the Norfolk area, widespread high tides were reported. Hampton Roads experienced the highest tides since 1936, including hurricane tides, and the highest tides of this century, excluding hurricane tides. Several city blocks in Norfolk were inundated and the water reached a depth of several feet in a few of the streets. Ocean-going transports and naval vessels were washed ashore due to the gale winds and high tides.

This storm pattern presented a combination of several features favorable for the development of high tides. The nearness of the two centers, their extreme intensities, and their paths apparently furnished essential ingredients for producing these extremely high tides. From 1230 GMT of the 11th to 0030 GMT of the 12th, the Gulf storm moved slightly north of east, passing just south of the North Carolina Capes, with the central pressure of the cyclone remaining nearly constant. Moving along this track it allowed a 10- to 15-mb. pressure differential to be maintained across the 2° of latitude from the low center to Norfolk, Va. This extremely strong pressure gradient produced gale winds from the east and north over Norfolk and vicinity that prevailed for nearly 14 hours. As the Gulf Low moved off the coast, the regenerated old cyclone was approaching the Norfolk area and with both centers of this April storm of approximately equal intensity there was no let up in the winds. In fact, the easterly fetch was increasing, bringing an even greater sweep of water toward the coast. The second center of this storm passed south of Norfolk in the late afternoon (EST) and at that time the highest tides since 1936 occurred at Hampton Roads.

9. PREDOMINANT STORM TRACKS FOR APRIL

Although numerous articles have been published concerning Gulf storms, there has been little work done concerning their normal tracks for the different months. As previously mentioned Saucier [1] found slightly less than one case of cyclogenesis per month for April in the Gulf of Mexico region. He further advised that movement of Gulf storms is usually to the east-northeast in winter and early spring during their formation and early history, with a distinct modal direction toward 70° or 80°. However, his frequency diagram on direction of motion from point of origin illustrates that an estimated one standard deviation, or approximately 67 percent of the population, had a course ranging from 40° to 95° with the remaining percentage covering a much wider spread of directions. Weightman [7] in his study of Gulf Coast storm tracks indicated the April track as being from the Mississippi Coast east-northeastward to near Wilmington, N. C., and thence north-northeastward paralleling the Atlantic Coast and moving into southern Maine. According to Klein [8] in a recent study of storm tracks the April frequency was not sufficient in the Gulf of Mexico area to arrive at any definite conclusions as to a principal track; he therefore omitted it from his chart. However, he prepared principal tracks of April cyclones moving off the east coast of the United States (his Chart 4). A secondary storm track along the North Carolina-Virginia border and another off the Carolina coast converge northeast of Cape Hatteras into a primary track beginning near 39° N., 70° W., then swinging slightly east of northeast. This takes the storms on a course about 100 miles south of Nova Scotia and Newfoundland. Klein further indicates a secondary track that branches northward from a point where the previously mentioned primary path begins. This secondary path extends northward over New Brunswick, Canada. It can easily be seen from figure 4 that the course of this Gulf of Mexico storm was considerably south of the principal east coast tracks.

The unusual southerly track of this storm can best be explained by the mean charts for the month and also by the 5-day mean charts prepared by the Extended Forecast Section. One of the most striking features of the charts of 5-day mean 700-mb. height departure from normal was the continued development of a blocking ridge (see fig. 6 of the preceding article by Dunn [9]), prior to and during the period now under study. During the period April 4–8, there was a positive anomaly of 330 feet near 70° N., 60° W. Moving slowly southward during the next 5-day period the positive anomaly was near 65° N., 57° W. or just east of the southern portion of Baffin Island. Curving anticyclonically, it was over southern Baffin Island during the period April 11–15, with the mean anomaly near +610 feet. For a complete trajectory of the 5-day mean positive anomaly, see figure 7 in the preceding article by Dunn [9]. During the period April 4–8 there was a negative anomaly of −410 ft. near 40° N., 41° W. This anomaly center had a mean value of −500 ft. by the middle of the April 7–11 period and was near 43° N., 51° W. By the middle of the 5-day period April 11–15 it was still located at 43° N., 51° W. with a mean value of −420 feet. Thus there was a total difference of over 1000 feet between the anomaly centers. This strong block caused the westerlies to be displaced farther south than normal for April and thus the storms during this period were deflected south of the normal April track.

10. APPLICATION OF PROGNOSTIC TECHNIQUES

Several objective, or semi-objective techniques for forecasting cyclone movement were reapplied in this investigation for comparison of results with the observed positions of the storm and the prognostic positions issued by the Joint Numerical Weather Prediction Unit (JNWP) and the National Weather Analysis Center (NWAC). Several factors made reapplication of the various techniques desirable: 1. It was not known which of the techniques the NWAC forecasters may have used in the initial preparation of their prognoses. 2. In research preparatory to this study it was necessary to make several large-scale revisions of frontal positions, central positions of the Lows, intensity of the Lows, and the tracks of the two Lows on the surface charts. 3. Similar revisions were necessary on the upper air charts. On many points this need for reanalysis became apparent only in the light of later data or the preparation of auxiliary charts used in this study and was not easily discernible at the time of the original analysis. Thus, it should be understood that these comparisons of the objective techniques are applied to the corrected or revised analyses and in that light may show a more comparable agreement with the actual happenings in this storm.

The surface prognostic techniques were applied on only the 1830 GMT chart of April 10 and the 0630 GMT chart of April 11 (figs. 1B and 2B). These two surface charts, with times corresponding to the charts upon which the NWAC 30-hour prognoses are based, were considered to be among the most critical in deciding the future path of this storm. This was especially true at 0630 GMT of April 11 for a continued northward or northeastward movement would have brought widespread rains north of Virginia along the eastern seaboard. Therefore, one of the prime reasons for making these computations was to determine if these objective techniques would have indicated the south-of-normal track that occurred with the surface Low and also the rapid eastward movement of the 500-mb. trough. An easy comparison of the results from the various techniques depicting the distance and direction that the prognostic centers were from the actual Low centers can be observed on the polar coordinate graphs in figure 6. These charts also contain the positions of the various prognoses of JNWP and NWAC.

On the surface charts the following techniques were investigated and their results were as indicated:

1. The Palmer method [11] when applied to the 1830 GMT chart indicated a track some 8° south of the observed route. On the 0630 GMT chart, the calculated direction was 6° north of the actual position. The Palmer technique does not give a forecast track nor the speed of movement, but rather "the line on which it will be found 30 hours later, regardless of the path it may follow or the distance it may travel during the period."

2. The Bowie and Weightman [12] method was also applied to the same two charts with these results: On the 1830 GMT map it gave a course some 28° south of the observed track and a movement which was much too slow. The 0630 GMT chart indicated the direction of the track as 4° too far to the north and the distance of the expected position was nearly 100 nautical miles too far east. It would be well to mention that in the summation of data for April, Bowie and Weightman had only one storm in the two 5° areas that were applicable for the 1830 GMT position.

3. The "normal" or climatological averages by Hering-Mount [13] were prepared for a period from November 1 through March 31. However, on examination of their table it was of interest to note that the highest speed indicated for the movements of Category IV Cyclones [3] occurred during the period of January 16–31. By pairing off the period adjacent to this date and continuing with other consecutive pairs, it was noted that the bimonthly period of November 1–15 could be paired with the period for April 1–15, and so an estimation of 21 m. p. h. was adopted. Using this assumed speed and the predetermined course of the "normal" technique, the path and distance obtained from the 1830 GMT chart was 9° south of the true path and 230 nautical miles from the observed center. A forecast from the 0630 GMT chart by this same technique indicated a course which was 9° to the north of the actual track and a position 220 nautical miles from the observed center. Both estimated movements were west of the actual positions.

4. The Hering-Mount technique [13] is a refinement of their "normal" or climatological average. "This forecast method is defined simply by averaging the past 12-hour velocity with the 'normal' speed to give the 30 hour predicted rate of movement, and the 12 hour isallobaric direction is averaged with the 'normal' direction of 52° to give the direction forecast." This technique produced two of the more accurate placements of the expected position. The 30-hour forecast from the 1830 GMT chart indicated a track 5° south of the observed course and the distance was 80 nautical miles southeast of the actual position. The track predicted from the 0630 GMT chart

[3] In the classification system devised by the meteorology staff of Eastern Air Lines [10], this storm would be typed a Category IV Cyclone, that is, "A cyclone that has been moving from the southwest quadrant and is located beneath a southwest flow aloft."

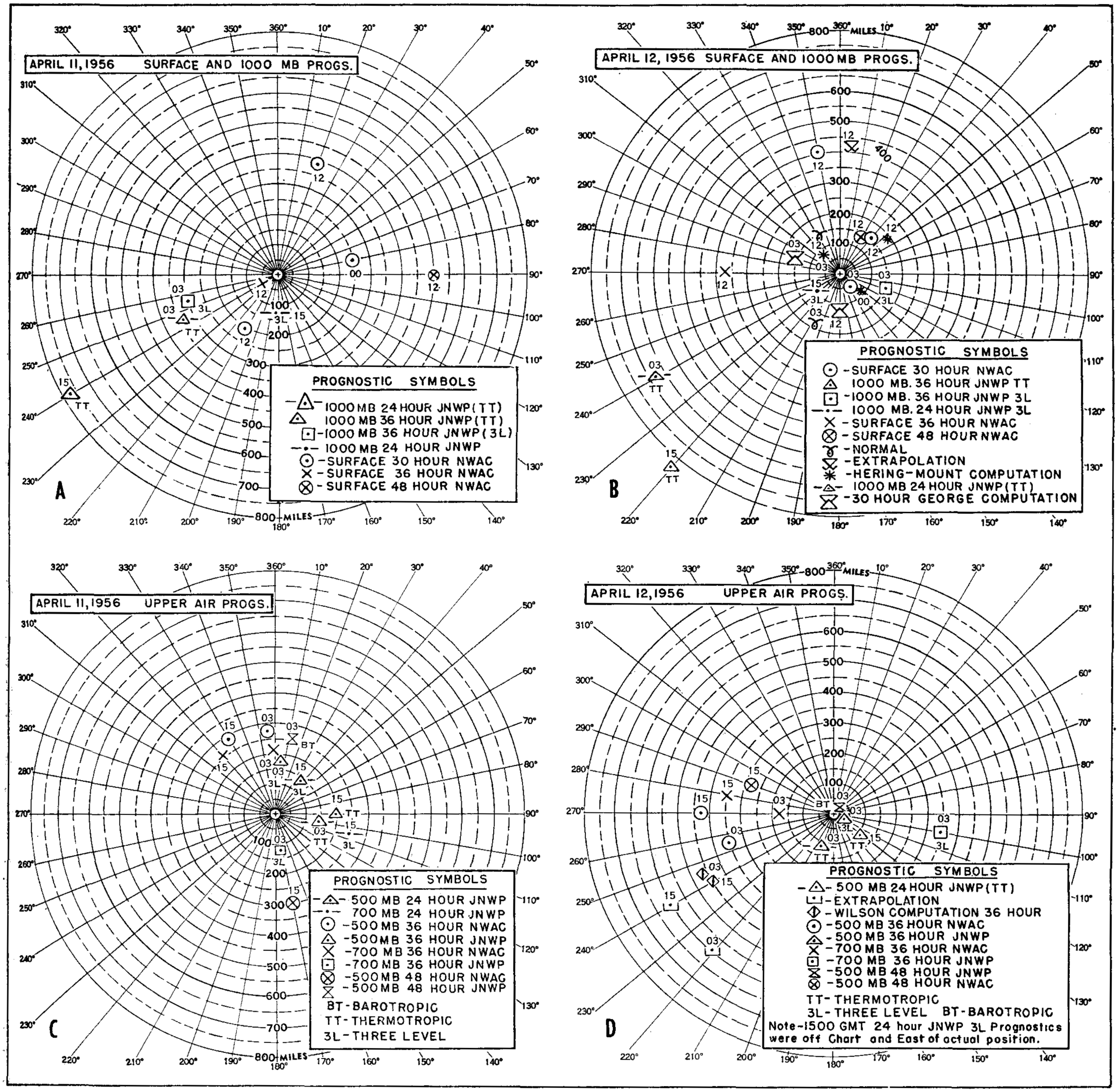

FIGURE 6.—A graphical picture of the errors in forecasts made by the various prognostic techniques tested or evaluated. The center of each graph represents the observed location of the Low. The distance and direction of deviation of the prognosis from the actual position is shown in nautical miles and degrees by the plotted positions of the different symbols. Identifying marks beside the symbols indicate prognostic techniques as follows: 3L=3 level; TT=thermotropic; BT=barotropic (all prepared by JNWP). Time of verification is next to the identifying character. (A) Surface and 1000 mb., April 11. (B) Surface and 1000 mb., April 12. (C) 700 and 500 mb., April 11. (D) 700 and 500 mb., April 12, 1956.

was 5° north of the actual path and the forecast position was 170 nautical miles southwest of the actual Low.

5. The Extrapolation method, using no anticipated curvature, produced an extremely large error on both charts. The 1830 GMT map indicated a path some 30° in error with the location of the forecast center some 700 nautical miles from the actual position. At 0630 GMT the estimated path was 20° in error and the distance from the actual center was 400 nautical miles. By this method, as in the preceding techniques, it is of interest to note

that when the storm path curved cyclonically the predicted course was south of the actual track, while when the track curved anticyclonically the deviation from the actual path was to the north of the observed track.

6. The George method, as derived by Shafer and Funke et al. [14] was also tried. The computation made from the 1830 GMT map indicated the Low should move on a course 10° north of the actual track, with the center after 30 hours, 150 nautical miles west-northwest of the actual position. The computation from the 0630 GMT chart indicated the Low would follow a path 10° south of the observed course, and at the end of 30 hours the predicted center was 120 nautical miles south of the actual position.

The George technique was the most decisive in predicting a path well to the south of the normal April track for surface Lows. It is of interest to note that the George system reversed the deflection noted in the first five of these objective methods.

A Petterssen pressure tendency computation [15] for this Low was not attempted since at least one sector was without actual pressure data and the interpreted values might have been in error. The pressure pattern was also complicated by the presence and movement of the old low center.

In the upper air, the 500-mb. level was used for computing the movement of the trough and the upper low center. The prognostic techniques tested were applied to the 500-mb. chart for 1500 GMT, April 10 and 0300 GMT, April 11. The objective methods that were applicable at this level were not nearly as numerous as for the surface, however the results of three of these systems are described below:

1. The use of straight extrapolation produced the poorest results as might be expected on a Low that at the time of prediction had not begun to recurve. It had been moving steadily from the northwest and west-northwest. The 36-hour extrapolation from the 1500 GMT 500-mb. chart placed the center 630 nautical miles southwest of the actual center. The 36-hour prediction from the 0300 GMT chart placed the position of the center 600 nautical miles west-southwest of the observed position of the Low.

2. The Wilson grid method [16] on the 1500 GMT chart predicted a track that was 22° south of the observed path and the forecast center was 460 nautical miles west-southwest of the actual center. The forecast from the 0300 GMT map indicated a track 17° south of the observed track and a center 450 nautical miles west-southwest of the actual center. The Wilson technique did not perform well for this type of situation and Wilson writes in his article, "when a surface wave development occurs ahead of the upper low, it causes the upper low to move faster than would be forecast by this method." However, it definitely indicated a track south of normal, even though the movement was slow due to such a surface wave development.

3. The Petterssen wave formula [17] produced satisfactory results in predicting the movement of the short-wave trough. A 36-hour forecast from the 1500 GMT 500-mb. chart indicated a position 130 nautical miles east of the observed trough. The prediction derived from the 0300 GMT map located the trough 70 nautical miles to the west of the actual trough at 1500 GMT, April 12.

These were the only methods of upper-air forecasting techniques that were used for direct comparison. Several of the other well known objective methods that would have been applicable to this situation were considered to be partly repetitious of the JNWP prognoses.

It must be realized that the comparisons of the objective techniques, the JNWP prognostic charts, the NWAC prognostic charts, and the actual positions of the storm center, either jointly or separately for a single storm, cannot be the basis for formulating any definite conclusions. However, it should be noted that all of the techniques applied indicated a line of movement that would carry the Low well offshore, with the exception of the Extrapolation method from the 0630 GMT chart of April 11.

11. NWAC AND JNWP PROGNOSES

There are three models currently in use by the JNWP Unit for numerically computed prognoses:

1. The baroclinic (Princeton 3-level) model for the 900-mb., 700-mb., and 400-mb. levels is computed for an area centered on and somewhat larger than the United States using a grid length of about 185 nautical miles and a time step of 30 minutes.

The 3-level (baroclinic) prognoses are prepared from the 1500 GMT upper air data and computed for 12-, 24-, and 36-hour periods. Forecast charts are printed out at these times for the 1000-mb., 700-mb., and 500-mb. levels from the computed data for the 900-, 700-, and 400-mb. levels. In this discussion, only the 24- and 36-hour prognoses were considered.

2. The barotropic (1-level) model for 500-mb. is computed for a large portion of the Northern Hemisphere using a grid length of about 350 nautical miles and a time step of 2 hours.

The 1-level barotropic prognoses are computed from the 0300 GMT upper air data. Three 500-mb. prognostic charts are printed out with verifying times occurring 24, 48, and 72 hours later.

3. The thermotropic (baroclinic 2-level) model for the 1000-mb. and 500-mb. levels is computed for approximately the same area as the barotropic model, using a grid length of 200 nautical miles and a time step of one hour.

The thermotropic prognoses are computed from the 0300 GMT upper air data and are printed out for the 1000-mb. and 500-mb. levels with verifying times of 12, 24, and 36 hours in advance. These forecasts are prepared only 4 days a week, Tuesdays through Fridays. It is pointed out that the thermotropic prognoses were initially released April 3, 1956 on an experimental basis. Therefore, the improbable positions forecast for the 1000-mb. low centers must be considered with that in mind; new planning to reduce these errors has since been adopted.

For further information concerning these numerical prognoses, JNWP Unit Bulletins may be consulted [18].

The subjective prognoses issued by NWAC include both the surface and upper air charts. The 30-hour surface prognoses are based primarily on the 0630 and 1830 GMT charts. The 36-hour surface prognosis is based mainly on the 0030 GMT surface chart and the 48-hour prognosis uses the 1230 GMT chart. There are two 36-hour 700- and 500-mb. prognoses prepared from the 0300 GMT and the 1500 GMT upper air charts. One 48-hour prognosis is based for the most part on the 0300 GMT chart, for verification almost 60 hours later.

With these facts in mind, let us now refer to figure 6. These diagrams were prepared without regard to the geographical position of the low centers on either the actual or prognostic charts. The central point indicates the location of the Low at the time the prognosis verified. The angle and distance of the plotted symbols from the central point represent the error in degrees and nautical miles from the actual low center.

The surface and 1000-mb. polar coordinate diagram (fig. 6A) indicates a wide dispersal in the forecasts from the actual position of the low center with only the 36-hour NWAC prognosis located within 100 nautical miles of the center.

The 700-mb. and 500-mb. polar diagram (fig. 6C) for April 11 illustrates how the area of dispersal has been considerably reduced.

On the 12th of April the surface and 1000-mb. diagram (fig. 6B) again presents a rather large dispersal pattern but there is a good concentration from the center to 200 nautical miles distant. It will be noted that on this diagram the 24-hour JNWP 3-level, the 30-hour NWAC, and one of the 30-hour Hering-Mount forecasts were located 100 nautical miles or less from the actual center.

Figure 6D presents the 700- and 500-mb. prognoses for April 12. The concentration of the JNWP forecasts was near the actual center with only the 700-mb., 36-hour, 3-level prognosis being much too fast; the baratropic 48-hour, thermotropic 36-hour, and the 3-level 36-hour forecasts were 100 nautical miles or less from the observed center. The NWAC forecasts indicated a movement nearly 10 knots less than the actual speed.

12. CONCLUSION

In concluding the discussion of this case, we shall summarize some of the salient aspects of the objective prognostic techniques. In this regard we have two questions to be answered. Would any of the more widely used objective prognostic techniques have forecast a course south of the normal April track? And if any of them would have predicted a southward departure, what would have been the deviation from the actual path of this storm and by which technique or techniques would the forecast have been made? A summation of these answers is as follows:

1. That all techniques used, with the exception of extrapolation, indicated that the movement would be south of the normal April track.

2. That the Bowie and Weightman, George, Hering-Mount, and Palmer techniques furnished the actual direction of movement of the surface low center with an error of 10° or less. All distances were 200 nautical miles or less from the actual center of the Low. The only exception to this was the Bowie and Weightman prognosis made from the 1830 GMT chart of the 10th.

3. That straight extrapolation was quite erroneous when used by itself.

4. That the tendency prevailed for these prognoses to be too far south of the actual track when the curvature was cyclonic and too far north of the track when the curvature was anticyclonic, with the reverse being true for the George technique. Whether this would prevail in a test of numerous cases is not known at this time.

5. That the average of the George and the Hering-Mount techniques produced the best results in this case. The errors were approximately zero direction and 50 nautical miles too slow on the forecast from the 1830 GMT chart of the 10th and zero direction and 80 nautical miles too fast for the prognoses from the 0630 GMT chart of the 11th.

6. That the distance the low center was forecast to move by the NWAC prognostic analyst would have alleviated the threat of heavy rain from Washington northward using any of the foregoing techniques with the exception of the straight extrapolation.

7. That the upper-air techniques investigated (Extrapolation, Petterssen, and Wilson) indicated either a position south of the actual route or an eastward projection of the trough in excess of the actual movement. There was no indication of any northward movement of the upper Low or trough in these cases.

8. That all of the JNWP prognoses, surface and aloft, for the 12th either had the low centers south of the actual track or had the trough position east of the low center.

9. That the block with its high positive anomaly west of Greenland and the large negative anomaly near 43° N., 51° W., resulted in a southward displacement of the westerlies. This type block is known to deflect storms south of their normal track.

10. That the NWAC prognosis for the direction of movement of this storm was unfavorably influenced by the analysis of the 0930 GMT surface chart. From this analysis it appeared that the Low development northwest of the Gulf storm center was a break-off Low from the Gulf of Mexico cyclone and not the old Low from the Memphis region undergoing rapid eastward displacement or regeneration.

Thus it appears from this study that a movement south of the normal April track could have been anticipated and forecast. Such a prognosis would have eliminated the prediction of heavy rains in the States north of Virginia.

It is thought that this sentence from the writings of the French mathematician Emil Borel is appropriate as a closing statement and as a reminder to all analysts and forecasters of weather. "Neither common sense, nor calculations, can insure us against misfortune, and it will always be a meager consolation for an individual to think that the probability of misfortune was slight, when he is the one to suffer from it."

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